HITRAP: A facility at GSI for highly charged ions [*]

H.-J. Kluge[a,b,†] T. Beier[a], K. Blaum[a,c], L. Dahl[a], S. Eliseev[a], F. Herfurth[a], B. Hofmann[a], O. Kester[a], S. Koszudowski[a], C. Kozhuharov[a], G. Maero[a], W. Nörtershäuser[a,c], J. Pfister[a,d], W. Quint[a], U. Ratzinger[d], A. Schempp[d], R. Schuch[e], T. Stöhlker[a], R.C. Thompson[f], M. Vogel[a], G. Vorobjev[a], D.F.A. Winters[a], and G. Werth[c]

[a]*Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[b]*Universität Heidelberg, Physikalisches Institut, D-69120 Heidelberg, Germany*
[c]*Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[d]*Johann Wolfgang Goethe-Universität Frankfurt, D-60438 Frankfurt, Germany*
[e]*Department of Atomic Physics, Frescativägen 24, Stockholm University, Sweden and*
[f]*Imperial College London, SW7 2AZ London, United Kingdom*
(Dated: February 5, 2008)

An overview and status report of the new trapping facility for highly charged ions at the Gesellschaft für Schwerionenforschung is presented. The construction of this facility started in 2005 and is expected to be completed in 2008. Once operational, highly charged ions will be loaded from the experimental storage ring ESR into the HITRAP facility, where they are decelerated and cooled. The kinetic energy of the initially fast ions is reduced by more than fourteen orders of magnitude and their thermal energy is cooled to cryogenic temperatures. The cold ions are then delivered to a broad range of atomic physics experiments.

Contents

I. THE PRESENT GSI FACILITY

The UNILAC at the Gesellschaft für Schwerionenforschung (GSI) produced its first heavy-ion beam in 1975. Today, the current GSI facility can provide quasi-continuous or pulsed beams of ions with practically any charge state, ranging up to U^{92+}, with kinetic energies of several MeV or GeV per nucleon. Figure 1 shows schematically the present GSI accelerator facility. The
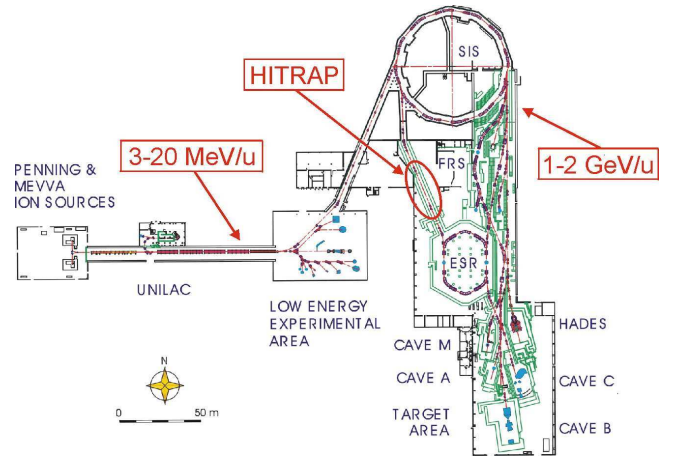
FIG. 1: The present GSI facility: highly charged ions are produced by a variety of different ion sources and accelerated by the linear accelerator (UNILAC) to several MeV/u. These fast ions can be used for low-energy experiments or can be injected into the heavy-ion synchrotron (SIS) where they are further accelerated. The SIS feeds the fragment separator (FRS), the experimental storage ring (ESR), or the fixed-target experiments in the different caves including that for heavy-ion tumor therapy. The HITRAP facility will be inserted into the re-injection channel, which can be used to feed the SIS with cooled highly charged ions from the ESR.

ions are produced by Penning, electron cyclotron resonance (ECR) and metal vapour vacuum arc (MEVVA) ion sources, and are then accelerated by a linear accelerator (UNILAC), which is roughly 120 meters long, to the first range of kinetic energies, *i.e.* up to several MeV/u. After the first acceleration stage, the ions can be delivered to a series of low-energy experiments. One example is SHIPTRAP, its name originating from the SHIP velocity filter that was used to discover six new elements: $^{264}_{107}$Bh (Bohrium, 1981), $^{269}_{108}$Hs (Hassium, 1984), $^{268}_{109}$Mt
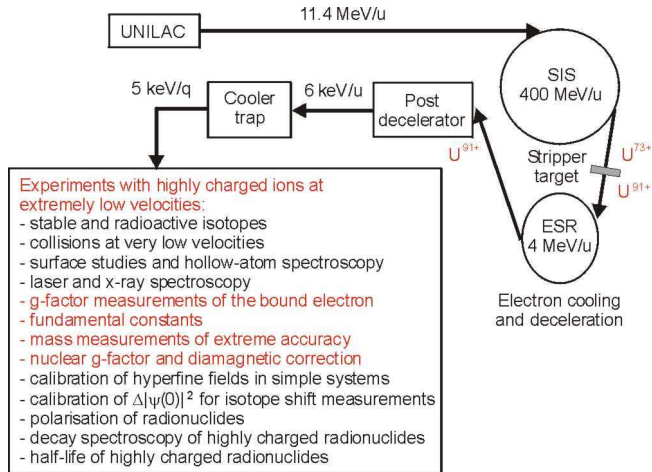
FIG. 2: Schematic of the HITRAP project: deceleration, trapping, and cooling of highly charged ions for a large variety of atomic physics experiments.

TABLE I: Participating teams in the HITRAP EU RTD Network. (RIMS: Recoil Ion Momentum Spectroscopy, HFS: HyperFine Structure).

Team	Leader	Task
Darmstadt, DE	H.-J. Kluge,	HITRAP facility
	O. Kester	
	W. Quint	
Orsay, FR	J.-P. Grandin	RIMS (H1)
Groningen, NL	R. Morgenstern,	ion-surface exp. (H2)
	R. Hoekstra	
Mainz, DE	G. Werth,	g-factor, mass (H4,H5)
	K. Blaum	
Krakow, PL	A. Warczak	x-ray spectroscopy (H3)
Stockholm, SE	R. Schuch	mass (H5)
Heidelberg, DE	J. Ullrich	RIMS (H1)
Vienna, AU	J. Burgdörfer	theory (H2)
London, UK	R.C. Thompson	HFS (H6)

(Meitnerium, 1982), $^{271}_{110}$Ds (Darmstadtium, 1994), $^{272}_{111}$Rg (Röntgenium, 1994), and $^{277}_{112}$Uub (Ununbium, 1996). SHIPTRAP is used to perform high-precision mass measurements of trapped (unstable) radionuclides with a relative mass uncertainty of $\delta m/m \approx 10^{-8}$.

In the heavy-ion synchrotron SIS the ions are accelerated to kinetic energies of up to 2 GeV per nucleon for atomic and nuclear physics experiments as well as heavy-ion tumor therapy. When using highly charged ions, ultra-high vacuum (UHV) conditions are crucial in order to avoid charge changing collisions. In the UNI-LAC, where the ions' charge states are not yet very high, pressures of around 10^{-6} mbar are sufficient. However, in the heavy-ion synchrotron SIS (216 m circumference) and in the experimental storage ring ESR (108 m circumference), for which the charge states are increased by shooting the highly-energetic ions through a stripper foil, the pressure is in the 10^{-11} mbar regime.

II. THE HITRAP PROJECT

As can be seen from Figure 1, the new trapping facility will be inserted into the re-injection channel between the ESR and the SIS. The new facility will broaden the current research field and open up several new ones, as indicated by the list in Figure 2. The combination of high charge states and very low kinetic energies makes it possible to (re)trap the ions in Penning traps, where the ions themselves can be studied with high precision, or to collide them with gases and surfaces, in order to study their interaction with neutral matter [1].

In order to prepare the HITRAP facility itself as well as the different experimental set-ups to be used at the HITRAP facility with low-energy highly charged ions, the HITRAP RTD Network was created, which was funded from 2001 through 2005 by the European Union. Within

this project, there were different teams (nine in total) from different countries, each team preparing an experiment, (see Table I), or providing theory. The goal of the HITRAP network was *the development of novel instrumentation for a broad spectrum of physics experiments with heavy highly charged ions (up to U^{92+}) at low energies (< 1 eV/u)*. Within this project, instrumentation was developed for high-precision measurements of atomic and nuclear properties, mass and g-factor measurements, and ion-gas and ion-surface interaction studies.

The construction of the HITRAP facility, which is being carried out in close collaboration between the GSI Divisions for Infrastructure, Accelerators and Atomic Physics and the Institute for Applied Physics at the University of Frankfurt, started in the beginning of 2005 when appropriate funds were available. Commissioning of the HITRAP facility is planned for the first half of 2008 so that the experimental teams can start to perform their experiments in the second half of 2008.

III. THE HITRAP FACILITY

The new trapping facility is shown schematically in Figure 3. The highly charged ions are accelerated in the SIS to typically 400 MeV/u, almost completely stripped and injected into the ESR. Here they are electron cooled as well as decelerated and a single bunch is created by bunch-merging. At an energy of 4 MeV/u, the ions are ejected out of the ESR as a bunch of about 10^5 ions, with a pulse length of 1 μs (roughly 1 m long) and enter the linear decelerator of HITRAP. The facility is designed to operate in a pulsed mode, which means that this cycle (filling the ESR, cooling, deceleration and ejection) will be repeated every 10 seconds. Before the ion bunch enters the LINAC and the radiofrequency quadrupole (RFQ) structure, the ion pulse is reshaped by the buncher (Fig-
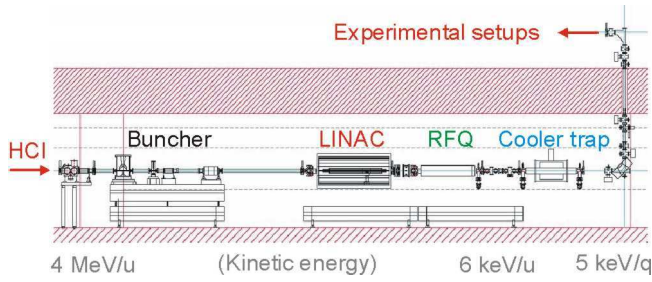
FIG. 3: Side view of the HITRAP facility. The highly charged ions come from the left and are decelerated by LINAC and RF quadrupole structures. They are injected at an energy of 6 keV/u into the Cooler Penning trap where they are trapped and cooled. After cooling to liquid-helium temperature they are ejected and transported with very low energies to the experiments on top of the platform.

FIG. 4: Photographs taken from the same position in the ESR Experimental Hall and showing the construction of the HITRAP platform. Left: situation in 2004 before construction. Middle: situation in 2005 when the platform was erected for the huts housing the electronics of the HITRAP facility and of the the HITRAP experiments, for RF power supplies and other devices. Right panel: situation in 2006 when the platform is ready, the huts are in place, and the installations are almost completed.

ure 3). After deceleration in the RFQ, the ions enter the Cooler (Penning) trap with only a few keV/u.

The Cooler trap operates in two steps for cooling the highly charged ions to liquid-helium temperature: electron cooling and resistive cooling. For the first step, there are sections with cold electrons that interact with the highly charged ions, thus dissipating the ions' kinetic energy. The electrons themselves cool by synchrotron radiation inside the cold bore of the superconducting magnet within a few seconds [2]. In the case of resistive cooling, the ions induce image charges in the trap electrodes. Connecting a frequency-resonant RLC-circuit to the trap electrodes allows for energy dissipation to this external cryogenic circuit. Resistive cooling is expected to take several seconds [3]. Finally, the trapped highly charged ions will have a thermal energy corresponding to slightly more than 4 K, due to noise in the electronic circuits. The cold ions are then transported, with kinetic energies of only a few keV/q, to the different setups installed on top of the re-injection channel as a high-quality ion beam.

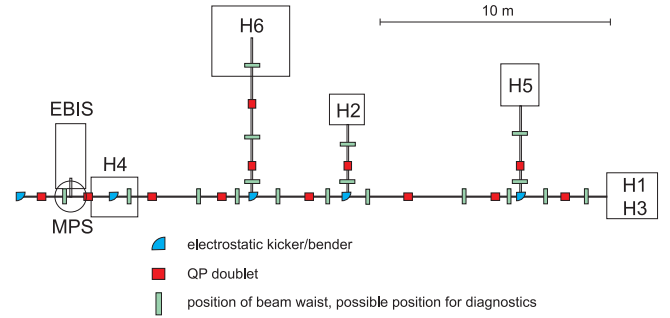A new platform was built inside the ESR experimen-

FIG. 5: Schematic overview of the beamline on the experimental platform. The experiments are indicated by the numbers H1-H6 (see Table I). Beam transport calculations have been performed leading to the arrangement of ion optical elements as shown in the figure. The ion beam enters this section from below and travels from the extreme left hand side to the right. The EBIS is an off-line ion source for tests of the systems, the MPS (multi-passage spectrometer) will feed the EBIS ion beam into the system when needed.

tal hall at GSI to house huts for electronics for the local control of the HITRAP facility and for the different HITRAP experiments and to provide space for the required infrastructure of the HITRAP facility such as supplies for radiofrequency, electricity and water. A hole was drilled through the concrete above the re-injection channel, which will be used for the beamline to transport the ions from the Cooler trap towards the setups. The construction of this platform is illustrated by the photo series in Figure 4.

For the HITRAP experiments, a complete network of beamlines and ion optical elements needs to be developed and constructed. Calculations of these elements and the beam transport have been carried out showing that nearly 100% transmission is possible. A scheme of the current layout of the experiments is shown in Figure 5. Most of the ion optical elements are designed. The elements for bending the ion beam, the so-called kicker-benders, are under construction. The beamline towards the experiments needs to have a vacuum of the order of 10^{-11} mbar or better to avoid charge exchange with residual gas. This puts severe demands on the materials used for the construction of the ion optical elements almost approaching those encountered when constructing an electrostatic UHV storage ring such as e.g. ELISA in Aarhus, Denmark [4].

Because the HITRAP facility will not be able to continuously obtain the ESR beam for testing the Cooler trap and the experimental setups, it was decided to install an electron beam ion source (EBIS), which was available from the University of Frankfurt, on the platform for off-line tests. This source (MAXEBIS) is currently being tested and will be used to tune the low-energy beam line (LEBT) towards the Cooler trap, and for tests of the Cooler trap itself. Afterwards, the components will be moved to the HITRAP facility. A more complete overview of the time planning for the construction of the

TABLE II: The time schedule for the HITRAP project.

Action	Date
Preparation of infrastructure (safety, media supply, controls, RF)	Ongoing
Delivery of the Cooler trap magnet	Spring 2007
Test of HITRAP low-energy beam transport and Cooler trap with EBIS	Mid 2007
Installation of buncher cavities in the re-injection channel	Spring 2007
First test of buncher cavities with beam from ESR	May 2007
Installation of LINAC cavities	Fall 2007
Commisioning of the LINAC	Spring 2008
Commissioning of HITRAP	Spring 2008
First experiments	2008

HITRAP facility is presented in Table II.

IV. EXPERIMENTS AT HITRAP

Since this publication is dedicated to Ingvar Lindgren on the occasion of his 75th birthday, out of the many experiments becoming possible (see inset of Figure 2), we discuss here only those which are very close to the heart of Ingvar Lindgren. These are the g-factor of the bound electron, the hyperfine structure, and the precision mass measurements. X-ray spectroscopy is discussed in a publication by T. Stöhlker *et al.* in the same volume [5]. In all these experiments, quantum electrodynamics plays a dominant role, and the progress in atomic theory is essential.
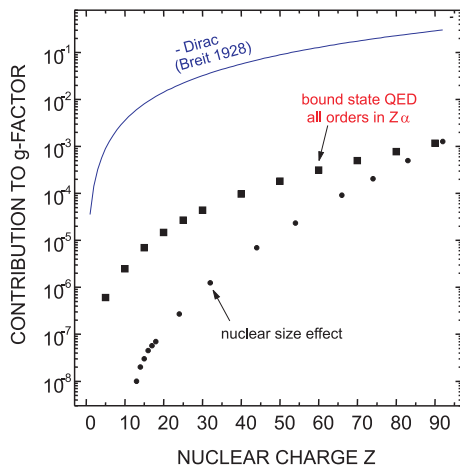

FIG. 6: Contributions to the g-factor versus nuclear charge Z. For heavy ions, the situation is more difficult, but also more interesting, since the QED and nuclear size contributions become comparable.

A. The g-factor of the bound electron

The precise measurement of the g-factor of the electron bound in a hydrogen-like ion is a sensitive test of bound-state QED at high fields. Highly charged ions are ideal for such studies, because the electromagnetic fields existing close to the nucleus are much higher than those which can be created artificially in a laboratory. For example, the electric field strength close to the nucleus of U^{91+} is of the order of 10^{16} V/cm, which is higher than those created by the strongest lasers available. At such high electromagnetic fields, perturbative QED calculations are no longer accurate, and higher-order terms need to be evaluated carefully. Unfortunately, in this regime there is little or no experimental data to compare the non-perturbative codes to. This is precisely why g-factor experiments are important.

In relativistic Dirac theory, the g-factor of an electron bound to a H-like ion is given by [6, 7]

$$g = \frac{2}{3}\left(1 + 2\sqrt{1-(Z\alpha)^2}\right),\qquad(1)$$

where Z is the nuclear charge and α the fine structure constant. The ratio of the bound-electron (g_{bound}) to the free-electron g-factor (g_{free}) can be expressed, to leading order in $Z\alpha$, as

$$\frac{g_{bound}}{g_{free}} \approx 1 - \frac{1}{3}(Z\alpha)^2 + \frac{1}{4\pi}\alpha(Z\alpha)^2.\qquad(2)$$

The first two terms in Eq. (2) are dominant and stem from Dirac theory, the third term comes from bound-state QED. Both contributions are indicated in Figure 6, and it can be seen that at high Z the QED term is of the same order of magnitude as the nuclear size effects. From Eq. (1) it is clear that for Z larger or equal to α^{-1}, g is undefined. Already when $Z \ll \alpha^{-1}$ is no longer valid, non-perturbative calculations have to be performed [8, 9]. Corresponding first calculations were initiated by I. Lindgren and G. Soff.

The g-factor of the bound electron in $^{12}C^{5+}$ [10] and $^{16}O^{7+}$ [11] has been obtained via spin-flip measurements of a single cold (4 K) ion. The setup was constructed in a GSI-Mainz collaboration, and consists of two Penning traps [12], *i.e.* a 'precision trap' and an 'analysis trap', placed in one superconducting magnet. A schematic of the trap is shown in Figure 7. The g-factor can be obtained from measurements of the cyclotron frequency $\omega_c = qB/M_i$ and the Larmor frequency $\omega_L = geB/(2m_e)$, since it can be expressed as

$$g = 2\left(\frac{q}{e}\right)\left(\frac{m_e}{M_i}\right)\left(\frac{\omega_L^e}{\omega_c^i}\right),\qquad(3)$$

where m_e, e and M_i, q, are the mass and charge of the electron and the ion, respectively. Using high-quality resonant circuits, the oscillation frequencies of an ion inside a Penning trap can be measured independently and with
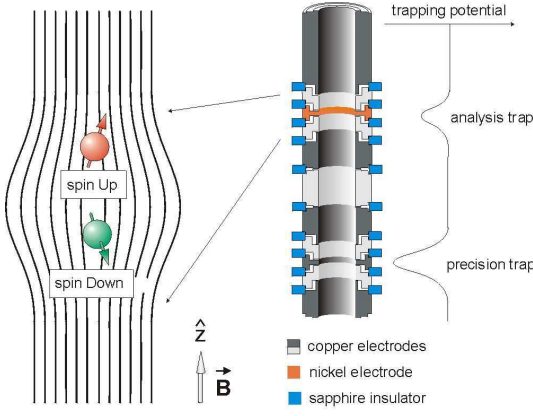
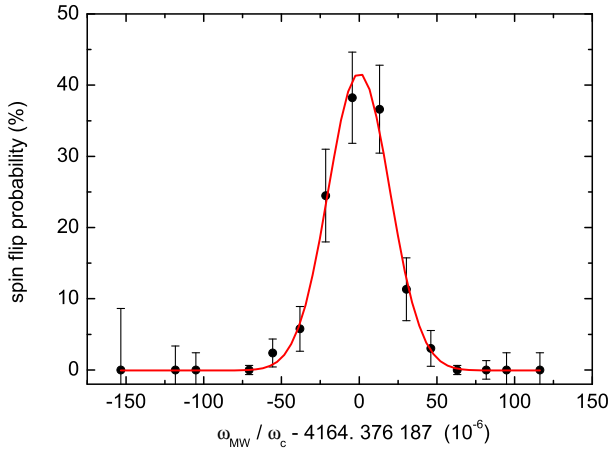FIG. 7: Schematic of the double Penning trap setup used for g-factor measurements of the bound electron.

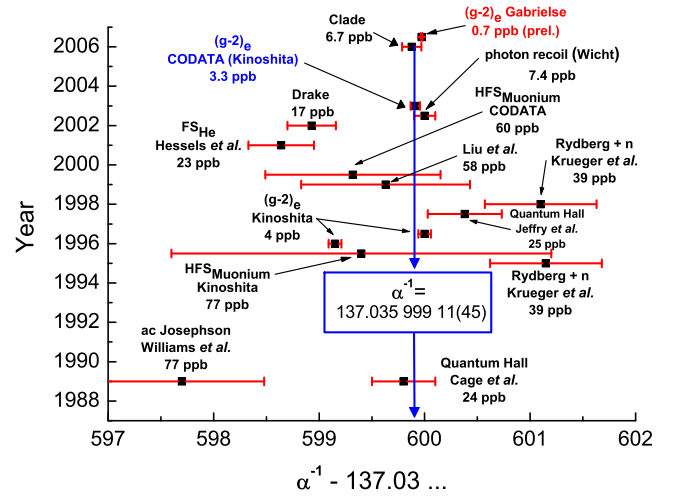FIG. 8: Larmor resonance of the g-factor measurement of the bound electron in $^{12}C^{5+}$ [10].

FIG. 9: Landscape of the fine structure constant α: the evolution of the different measurements and their accuracies during the last 20 years is indicated.

the calculated values [7, 13]. The g-factor of the 1s electron thus enabled a test of bound-state QED at a level of 0.25%.

Accurate g-factor measurements also provide means to obtain better values for fundamental constants, such as the fine structure constant α (Figure 9). For example, because of the good agreement with theory, the g-factor data led to a determination of the electron mass with a four times higher accuracy [14]. The relative experimental accuracy $\delta m/m$ of this measurement was as good as 6×10^{-10}.

From Eq. (1) it can be seen that the g-factor is linked to α, and it can easily be shown that the relative uncertainty in α is correlated to that in g via

$$\frac{\delta\alpha}{\alpha} \propto \frac{1}{(Z\alpha)^2}\frac{\delta g}{g}. \qquad (4)$$

It is therefore most interesting to measure g at the highest possible Z. Succeeding the measurements in $^{12}C^{5+}$ [10] and $^{16}O^{7+}$ [11], a measurement of the electronic g-factor in $^{40}Ca^{19+}$ [15] is currently being prepared. When HITRAP is operational, similar experiments on heavy systems like $^{238}U^{91+}$ will be performed. It is expected that, from such a measurement, α (Figure 9) can be obtained with an accuracy of 10^{-8} [16]. A combination of such measurements in H-like and B-like heavy ions can increase this accuracy significantly [17].

B. Precision mass measurements

Masses of stable or radioactive nuclides can be measured with very high accuracy and single-ion sensitivity, using Penning traps [18, 19]. Since the cyclotron frequency of a trapped ion increases with the charge state,

high accuracy. For these measurements, the polarisation of the electron spin is 100%, because only one ion is used. The cyclotron frequency ω_c is determined inside the precision trap, and a spin-flip may be induced by microwave irradiation at a frequency close to the Larmor frequency ω_L. Detection of a spin-flip takes place after transporting the ion to the analysis trap. Here, a significant inhomogeneity of the magnetic field, produced by a nickel ring, makes the z-motion of the ion sensitive to the spin direction. The frequency of the z-motion is detected via electronic detection (based on image charges). After analyzing the spin direction, the ion is transported back to the precision trap for the next measurement cycle.

The experimental result obtained for a g-factor measurement of a single $^{12}C^{5+}$ ion is presented in Figure 8. The horizontal axis shows the ratio of the microwave frequency ω_{MW} to the cyclotron frequency ω_c, from which the g-factor of the bound electron can be obtained. The experimental g-factors of the hydrogen-like ions $^{12}C^{5+}$ [10] and $^{16}O^{7+}$ [11] agree within the uncertainties, which are dominated by the accuracy of the electron mass, with

highly charged ions provide better resolution and potentially also higher accuracy than singly charged ions. The SMILETRAP group in Stockholm has pioneered the use of highly charged ions in ion traps for mass spectrometry [20, 21, 22]. They measured the masses of several ions, which are important for tests of QED or double-beta decay, with an uncertainty close to 10^{-10}. Using the mass of $^{12}C^{6+}$, Van Dyck et al. [23] in Seattle measured the masses of stable singly charged ions with an accuracy of about 10^{-10}. A similar accuracy was obtained for the proton-antiproton comparison at CERN, measured by the group of Gabrielse [24]. Pritchard et al. [25] at MIT even had a mass spectrometer, which is now at Florida State University [26], with an accuracy of about 10^{-11}. The masses of singly charged radionuclides have been measured with an accuracy of 10^{-7} to 10^{-8} and better, by Penning trap mass spectrometers installed at ISOLDE/CERN [27, 28], Argonne [29], Jyväskylä [30], MSU [31], and GSI [32]. Highly charged ions for mass spectrometry will be used at TITAN at ISAC/TRIUMF, Vancouver [33], LEBIT/MSU [34], HITRAP/GSI [35], ISOLTRAP/ISOLDE [36], MAFFTRAP/Munich [37], and at MATS/GSI [19].

Table III shows a comparison between a mass measurement in a Penning trap with a singly charged ion, and one with a highly charged ion. The numbers show that, for the same isotope, an ion with a charge of $q = 50$ already leads to an improved mass resolution of nearly two orders of magnitude. Longer observation times (for example, $T_{obs} \geq 10$ s) and higher charge states (i.e. $q = 92$ for uranium) can further improve the mass resolution. In principle, a mass measurement accuracy of 10^{-11} or better can be reached. This would, for example, make it possible to 'weigh' the $1s$ Lamb shift in U^{91+} with an accuracy better than presently possible by x-ray spectroscopy [38].

TABLE III: Comparison of the accuracy of mass measurements for a singly and a highly charged ion with mass $A = 100$ in a magnetic field of $B = 6$ T. ν_c is the cyclotron frequency, T_{obs} the observation time of a measurement, R is the resolving power given by the ratio $\nu_c/\delta\nu_c$, and $\delta m/m$ is the relative mass uncertainty.

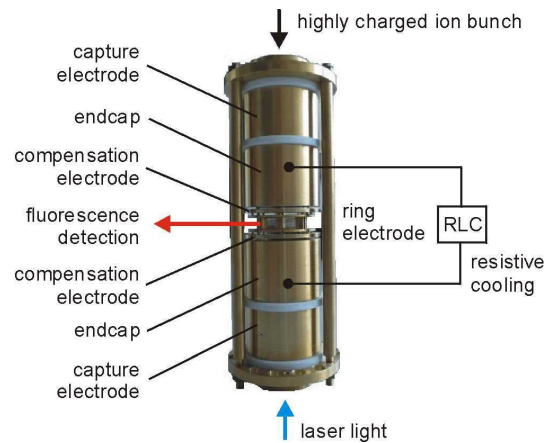| singly charged ion	
$q = 1$	$\nu_c = 1$ MHz
$T_{obs} = 1$ s	$\delta\nu_c = 1$ Hz
$R = 10^6$	$\delta m/m \approx 10^{-8}$
highly charged ion	
$q = 50$	$\nu_c = 50$ MHz
$T_{obs} = 1$ s	$\delta\nu_c = 1$ Hz
$R = 5 \times 10^7$	$\delta m/m \approx 2 \times 10^{-10}$

FIG. 10: Photograph of the spectroscopy trap, which will be used for laser spectroscopy measurements of hyperfine splittings in highly charged ions. The ring electrode is split into four segments, which are covered by highly transparent mesh.

C. Laser spectroscopy of hyperfine structure

An experiment is being prepared to perform laser spectroscopy of ground state hyperfine structure in highly charged ions [39]. Normally, the hyperfine splitting wavelength in atoms and ions is in the microwave region. However, since the hyperfine splitting of hydrogen-like ions scales with the nuclear charge as Z^3, the hyperfine structure becomes measurable by laser spectroscopy above $Z \approx 60$. This allows for accurate laser spectroscopy measurements of these hyperfine splittings and, in turn, for sensitive tests of corresponding calculations of transition energies and lifetimes. Previous measurements were carried out for $^{209}Bi^{82+}$ [40], $^{165}Ho^{66+}$ [41], $^{185,187}Re^{74+}$ [42], $^{207}Pb^{81+}$ [43], $^{209}Bi^{80+}$ [44] and $^{203,205}Tl^{80+}$ [45]. These measurements suffered from the Doppler width and shift of the transition, which were due to the relativistic velocities and velocity spreads of the ions in the ESR. In the case of the measurements conducted in the EBIT (electron beam ion trap) at Livermore, resonance transitions were broadened due to the high temperatures of the ions in the EBIT. The new experiments will be performed in a Penning trap with confined and cold highly charged ions at cryogenic temperatures. This strongly reduces the Doppler effects and will lead to a measurement resolution of the order of 10^{-7}. Hence, these results will allow the determination of hyperfine anomalies which requires high precision. The trapped ions will be laser-excited along the trap axis, and fluorescence detection will take place perpendicular to the trap axis, through the transparent ring electrode (see Figure 10).

Furthermore, by use of a rotating wall technique [46], which radially compresses the ion cloud via a rotating dipole field applied to the segmented ring electrode, a high ion number density can be obtained. Together with the localisation, this enhances the intensity of the measured fluorescence. For an ion cloud of 10^5 highly charged

ions at the space charge limit of the trap, we calculated fluorescence rates of several thousand counts per second on a background of a few hundred counts per second (S/N $\approx$ 50) [47]. Laser intensities of several tens of W/m^2 are required to saturate the 10 mm^2 ion cloud, which implies moderate laser powers of just a few mW [39].

Furthermore, measurements of hyperfine structure in H- and Li-like ions can test quantum electrodynamics (QED) at high electromagnetic fields [48]. Such accurate measurements can be compared to corresponding calculations that include nuclear effects, such as the Bohr-Weisskopf and Breit-Schawlow effects, as well as (higher-order) QED effects. From a comparison of the hyperfine splitting in H- and Li-like ions of the same isotope, the nuclear effects cancel to a large extent, thus enabling a stringent test of the QED effects [48]. The necessary experimental resolution for such a comparison is of the order of 10^{-6}, which can relatively easily be met by laser spectroscopy [49].

V.   THE NEW GSI FACILITY

In the more distant future, HITRAP will be a component of the new international Facility for Antiproton and Ion Research (FAIR) [50]. HITRAP will thus, in addition to highly charged and radioactive ions, also produce low-energy antiprotons. Furthermore, the FAIR facility will provide the highest intensities of both stable and radioactive ion beams with energies up to 34 GeV per nucleon. At such energies, the highly charged ions generate electric and magnetic fields of exceptional strength and ultra-short duration. The general layout of FAIR is shown in Figure 11.
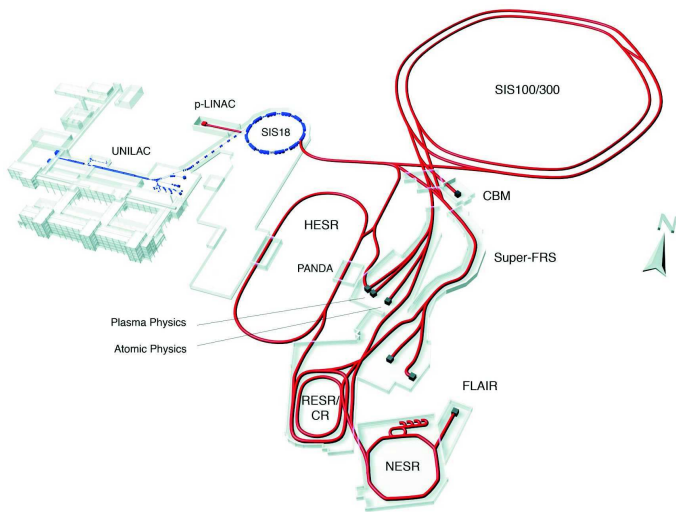

FIG. 11: The future GSI facility FAIR (Facility for Antiproton and Ion Research) in Darmstadt.

A.   Stored Particle Atomic Research Collaboration (SPARC)

The new FAIR facility has key features that offer a range of new opportunities in atomic physics research and related fields, which will be exploited by the Stored Particle Atomic Research Collaboration SPARC [51]. In particular, the Superconducting Fragment Separator (SFRS) will provide a rich spectrum of radionuclides. The high intensity of secondary beams produced at the SFRS will make it possible to extract decelerated radioactive ion beams from the New Experimental Storage Ring (NESR) and to decelerate them for trap experiments with sufficient intensity at HITRAP. Therefore, the physics program of HITRAP can be extended to novel experiments with trapped radioactive ions and, of course, with trapped antiprotons. Trapped radioactive ions in high charge states may reveal a completely new domain for fundamental interaction studies and for experiments on the borderline between atomic and nuclear physics.

Moreover, the manipulation of trapped radioactive ions with laser light opens up possibilities to study questions of the Standard Model. By optical pumping within the hyperfine levels of the ground state, the nuclear spins of radioactive nuclides can be polarized with high efficiency. The detection of the asymmetry of beta decay, for example, will allow one to explore deviations from the vector/axial-vector (VA)-structure of the weak interaction and to set limits for the masses of heavy bosons, which are not included in the Standard Model.

Direct mass measurements on unstable nuclides with ultra-high accuracy (up to $\delta m/m \approx 10^{-11}$) will also be possible. Such an accuracy would allow one to determine the binding energy of U^{91+} with an accuracy of $\delta mc^2 \approx 2eV$. If the QED calculations are found to be correct, nuclear charge radii of unstable nuclides can be determined.

For a general exploration of masses in the chart of nuclei, a mass resolution of $\delta m/m \approx 10^{-6}$ to 10^{-7} is sufficient. This is also planned by isochronous or Schottky mass spectrometry experiments at the New Experimental Storage Ring (NESR). However, in some cases, like double-beta decay or tests of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix, a much higher accuracy is required, which is possible by using trapped highly charged ions at HITRAP [35] and at MATS [19].

B.   Facility for Low-Energy Antiproton and Ion Research (FLAIR)

The planned FLAIR facility will be the most intense source of low-energy antiprotons world-wide [52]. The beam intensity of extracted low-energy antiprotons will be two orders of magnitude higher than that of the Antiproton Decelerator (AD) at CERN. We therefore anticipate that experiments with trapped antiprotons, which are currently impossible anywhere else (due to insufficient

intensities), will be performed at the FLAIR facility. A possible highlight in the field of low-energy antimatter research would be the first direct experimental investigation of the gravitational interaction of antimatter, which has never been attempted up to now. Such investigations could be performed on ultra-cold antihydrogen atoms [53] which are produced by recombining trapped antiprotons with positrons in a so-called nested Penning trap. The effect of gravity on antimatter is an important issue for the development of quantum theories of gravity.

[1] T. Beier *et al.*, Nucl. Instr. Meth. Phys. Res. B **235** (2005) 473.

[2] J. Bernard *et al.*, Nucl. Instr. Meth. Phys. Res. A **532** (2004) 224.

[3] G. Maero, private communication (2006).

[4] S.P. Møller, Nucl. Instr. Meth. Phys. Res. A **394** (1997) 281.

[5] T. Stöhlker *et al.*, Advances in Quantum Chemistry, Vol 53, ed. S. Salomonson and E. Lindroth, Elsevier, (2007) 57.

[6] G. Breit, Nature 122 (1928) 649.

[7] T. Beier, Phys. Rep. **339** (2000) 79.

[8] S.A. Blundell *et al.*, Phys. Rev. A **55** (1997) 1857.

[9] H. Persson *et al.*, Phys. Rev. A **56** (1997) R2499.

[10] H. Häffner *et al.*, Phys. Rev. Lett. **85** (2000) 5308.

[11] J. Verdú *et al.*, Phys. Rev. Lett. **92** (2004) 093002.

[12] H. Häffner *et al.*, Eur. Phys. J. D **22** (2003) 163.

[13] T. Beier *et al.*, Phys. Rev. A **62** (2000) 032510.

[14] T. Beier *et al.*, Phys. Rev. Lett. **88** (2002) 011603.

[15] M. Vogel *et al.*, Nucl. Instr. Meth. Phys. Res. B **235** (2005) 7.

[16] V.M. Shabaev and V.A. Yerokhin, Phys. Rev. Lett. **88** (2002) 091801.

[17] V.M. Shabaev *et al.*, Phys. Rev. Lett. **96** (2006) 253002.

[18] D. Lunney *et al.*, Rev. Mod. Phys. **75** (2003) 1021.

[19] K. Blaum, Phys. Rep. **425** (2006) 1.

[20] R. Jertz *et al.*, Z. Phys. D **21** (1991) S179.

[21] T. Fritioff *et al.*, Int. J. Mass Spectrom. 251 (2006) 281.

[22] S. Nagy *et al.*, Phys. Rev. Lett. **96** (2006) 163004.

[23] R.S. Van Dyck Jr. *et al.*, Int. J. Mass Spectrom. **251** (2006) 231.

[24] G. Gabrielse, Int. J. Mass Spectrom. **251** (2006) 273.

[25] J.K. Thompson *et al.*, Nature **430** (2004) 58.

[26] M. Redshaw *et al.*, Int. J. Mass Spectrom. **251** (2006) 125.

[27] F. Herfurth *et al.*, Phys. Rev. Lett. **87** (2001) 142051.

[28] M. Mukherjee *et al.*, Phys. Rev. Lett. **93** (2004) 150801.

[29] G. Savard *et al.*, Int. J. Mass Spectrom. **251** (2006) 252.

[30] T. Eronen *et al.*, Phys. Lett. B **636** (2006) 191.

[31] G. Bollen *et al.*, Phys. Rev. Lett. **96** (2006) 152501.

[32] C. Rauth *et al.*, Phys. Rev. Lett. (2006), submitted.

[33] J. Dilling *et al.*, Int. J. Mass Spectrom. **251** (2006) 198.

[34] G. Bollen, private communication (2006).

[35] F. Herfurth *et al.*, Int. J. Mass Spectrom. **251** (2006) 266.

[36] A. Herlert *et al.*, Int. J. Mass Spectrom. **251** (2006) 131.

[37] D. Habs, private communication (2006).

[38] A. Gumberidze *et al.*, Phys. Rev. Lett. **94** (2005) 223001.

[39] M. Vogel *et al.*, Rev. Sci. Instrum. **76** (2005) 103102.

[40] I. Klaft *et al.*, Phys. Rev. Lett. **73** (1994) 2425.

[41] J.R. Crespo López-Urrutia *et al.*, Phys. Rev. Lett. **77** (1996) 826.

[42] J.R. Crespo López-Urrutia *et al.*, Phys. Rev. A **57** (1998) 879.

[43] P. Seelig *et al.*, Phys. Rev. Lett. **81** (1998) 4824.

[44] P. Beiersdorfer *et al.*, Phys. Rev. Lett. **80** (1998) 3022.

[45] P. Beiersdorfer *et al.*, Phys. Rev. A **64** (2001) 032506.

[46] W.M. Itano *et al.*, Science **279** (1998) 686.

[47] D.F.A. Winters *et al.*, Nucl. Instr. Meth. Phys. Res. B **235** (2005) 201.

[48] V.M. Shabaev *et al.*, Phys. Rev. Lett. **86** (2001) 3959.

[49] D.F.A. Winters *et al.*, Can. J. Phys. **85** (2007) 403.

[50] *An International Accelerator Facility for Beams of Ions and Antiprotons*, Conceptual Design Report November 2001, http://www.gsi.de/fair/overview/info/index_e.html.

[51] T. Stöhlker *et al.*, Nucl. Instr. Meth. Phys. Res. B **235** (2005) 494.

[52] E. Widmann, Comments on Atomic, Molecular and Optical Physics, Phys. Scr. **72** (2005) C51-C56.

[53] J. Walz and T.W. Hänsch, Gen. Rel. Grav. **36** (2004) 561.